Journal of Integrative Neuroscience, Vol. 10, No. 2 (2011) 189–202
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DOI: 10.1142/S0219635211002695

EFFECTS OF WI-FI SIGNALS ON THE P300 COMPONENT OF EVENT-RELATED POTENTIALS DURING AN AUDITORY HAYLING TASK

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Received 25 September 2010
Accepted 7 February 2011

The P300 component of event-related potentials (ERPs) is believed to index attention and working memory (WM) operation of the brain. The present study focused on the possible gender-related effects of Wi-Fi (Wireless Fidelity) electromagnetic fields (EMF) on these processes. Fifteen male and fifteen female subjects, matched for age and education level, were investigated while performing a modified version of the Hayling Sentence Completion test adjusted to induce WM. ERPs were recorded at 30 scalp electrodes, both without and with the exposure to a Wi-Fi signal. P300 amplitude values at 18 electrodes were found to be significantly lower in the response inhibition condition than in the response initiation and baseline conditions. Independent of the above effect, within the response inhibition condition there was also a significant gender X radiation interaction effect manifested at 15 leads by decreased P300 amplitudes of males in comparison to female subjects only at the presence of EMF. In conclusion, the present findings suggest that Wi-Fi exposure may exert gender-related alterations on neural activity associated with the amount of attentional resources engaged during a linguistic test adjusted to induce WM.

Keywords: Wi-Fi; P300 ERP component; Hayling; gender; EMF.

1. Introduction

Concern of health effects due to EMF, specifically radiofrequency (RF) exposure is currently arising. Numerous studies have investigated the potential effects of EMF,

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mainly those emitted by GSM mobile phones (Global System for Mobile communications) on cognitive functioning.

In a recent meta-analytic review [1], taking into consideration 19 studies, it was concluded that EMFs may have a small impact on human attention and working memory without clarifying the exact nature of this impact. In particular, it has been reported that human attention measured by the subtraction task was mildly affected in regard to decreased reaction time. Additionally, working memory being measured by the N-back test seems to be affected. The significant effects concerning the N-back test for working memory showed discrepant effect sizes: under condition 0-back, target response time was lower under exposure, while under condition 2-back, target response time increased. The number of errors under condition 2-back for non-targets appears to be higher under exposure. At other levels of the N-back test, no significant effect sizes were detected.

Event-related potentials (ERPs) are one of the most informative and dynamic methods of monitoring the information stream in the living brain. Because of the high time resolution, ERPs allow the investigation of the time course of auditory processing down to the scale of milliseconds. The P300 component of ERPs is thought to reflect attentional operation resources when working memory (WM) updating is engaged [13, 33, 48]. The P300 amplitude is thought to index attentional processing of target stimulus events — phenomena that appear related to memory processing, while the P300 peak latency is proportional to the time required to detect and evaluate a target stimulus [18, 36, 48].

As far as the effects of EMFs on the P300 component are concerned, the existing literature is rather conflicting. During an oddball task no effect has been found on the P300 component under the exposure of pulsed, GSM or Universal Mobile Telecommunications System (UMTS) signals [31, 55]. However in another study which examined the effects of electromagnetic fields emitted by GSM mobile phones on the human P300 component during an auditory task, results suggested that mobile phone exposure may affect neural activity [22].

A series of studies by our team provided evidence that it is necessary to examine the possible impact of EMF on brain activity separately for males and females, in order to unveil the possible confounding effects of gender and its interaction with EMF [24, 41, 46].

As far as Wi-Fi signals are concerned, due to the fact that daily public exposure to such signals increases rapidly, several investigations on its potential adverse health effects and dosimetry studies are ongoing [11, 17], although the exposure level is low compared to other sources [37].

In view of the above considerations, it can be hypothesized that the electrophysiological brain activity, as reflected by P300, in association with cognitive task operations, could be of value in identifying possible pathophysiological alterations evoked by Wi-Fi signals and their connection with gender. Thus, the present study was designed to determine whether the presence of Wi-Fi signals affects the patterns of P300 ERP component elicited during a Hayling Sentence Completion test adjusted to induce working memory (WM) operation [3, 5, 6]. Contemporary neuropsychological views define WM as the capacity to keep information "online" as necessary for an ongoing task [2, 10]. Accordingly, WM is thought to be in the service of complex cognitive activities, such as reasoning, monitoring, problem solving, decision making, planning, and searching/shifting the initiation or inhibition response, thus comprising (among others) a central executive system [19, 38, 40].

2. Materials and Methods

2.1. *Participants*

Thirty healthy individuals (15 men and 15 women, mean age = 23.76 ± 1.67 years, mean education = 16.9 ± 1.06 years) participated in the experiment. The participants were homogeneous with regards to age and educational level and had no history of any hearing problem. Informed consent was obtained from all subjects.

2.2. *Hayling sentence completion test*

The modified version of the Hayling Sentence Completion test used in the present study is made up from three different conditions: response initiation, response inhibition and baseline. In the response initiation condition, participants completed auditory presented sentences with a word clearly suggested by the context. In the response inhibition condition, participants produced a word that made no sense in the context of an auditory-presented sentence from which the last word was missing. Finally in the baseline condition, subjects were asked to repeat the last word of the presented sentence. The sentences were presented through earphones to the participants and the administration order of the three conditions was counterbalanced. The duration of the sentences was from 3–5 s. After the presentation of each sentence, there was a 500-ms EEG recording period, then a warning stimulus (100-ms duration, 65 dB, 500 Hz) was given, followed by an interval of 900 ms; the warning stimulus was then repeated. Individuals were instructed to give their response after the conclusion of the second warning stimulus. Each condition of the task contained 30 sentences. Before the ERP recording, there was a training period for each condition of the Hayling test in order for the participants to comprehend the nature of a correct response.

It should be noted that the task design involved the 1600-ms period after the participants had heard the sentence and before they were required to respond, in order to avoid interference during the recording session. The onset of ERP recording was 500 ms after the end of the auditory presentation of the sentence (Table 1).

2.3. *EMF exposure*

The subjects performed the tasks twice, with and without radiation, with an interval of two weeks between the measurements. The order in which the subject was exposed

Table 1. Sequence of events in each experimental trial.

Sequence of Action	Duration of Action
Auditory sentence presentation	3–5 s
EEG recording	500 ms
Warning stimulus*	100 ms
ERP recording*,†	1 s
Warning stimulus repetition	100 ms
Response onset	Within 5 s
Period between response completion and onset of next sentence presentation	4–9 s

Notes: *Simultaneous onset of warning stimulus and of ERP recording.
†Peak amplitudes were measured relatively to the mean amplitude of the 100 ms pre-stimulus baseline period; latency measurements were computed relatively to warning stimulus onset.

at the EMF (exposure at the first or second visit) was random. The EMF was emitted by a Wi-Fi access point that was operating at 2.45-GHz frequency. The access point was present at both tasks and the subjects were blinded to the presence or absence of the radiation. The Wi-Fi signal was radiated by a dual dipole antenna, with 20-dBm power and orthogonal frequency-division multiplexing (OFDM) modulation. The access point was placed at a distance of 1.5 m from the head. The field strength was 0.49 V/m at the point where the subjects' head was standing. According to Kapareliotis *et al.* [29] there is no evidence that a Wi-Fi signal causes interference at the EEG recording at the distance of 1.5 m from the EEG electrodes.

The experiment was conducted in a Faraday room, which screened any electromagnetic interference that could affect the measurements. The attenuation of the mean field was more than 30 dB.

2.4. *Recordings*

Electroencephalographic (EEG) activity was recorded from 30 scalp Ag/AgCl electrodes (F7, FC5, C3, CP1, P3, Fpz, Afz, Cz, O1, O2, F8, FC6, T4, CP2, P4, CP6, T6, F3, FC1, T3, CP5, T5, FP1, FP2, Fz, Pz, Oz, F4, FC2, C4) based on the International 10–20 system of electroencephalography [26]. Linked ear lobes served as reference. Electrode resistance was kept constantly below 5 kΩ. The bandwidth of the amplifiers was between 0.05–35 Hz in order to avoid interference of the power supply network's signal, which is at 50 Hz. Eye movements were recorded with the use of electro-oculogram (EOG) and recordings with EEG higher than 75 μV were excluded. The evoked biopotential signal was digitalized at a sampling rate of 1 kHz and was averaged by a computerized system.

The signals were recorded for a 1500-ms interval, which means 500 ms before the first warning stimulus (EEG) and 100 ms after that (ERP).

2.5. *Data transformations*

For each question, 1500 data points, each corresponding to time segments of 1 ms duration for each electrode, were saved. This procedure was done separately for each EMF condition. The final data for analysis for each subject and condition consisted of 1500 amplitude values for each electrode, expressed in μVolts corresponding to the 1500 ms of the time period [46], 500 ms before the onset of the first warning stimulus (EEG), and 1000 ms after the onset (ERP).

In order to optimize the signal-to-noise ratio for each subject, each channel ERP amplitudes were averaged using the voltage over the 100-ms pre-stimulus epoch as the baseline. An algorithm was used for identifying the amplitude and latency of the positive peak between 220 and 500 ms after the onset of the first warning stimulus. The sLORETA software was used to calculate and compare the relevant scalp maps [43, 47].

2.6. *Statistical analysis*

The values of the P300 amplitudes at the 30 leads were subjected to multivariate analysis of variance (MANOVA) with the three Hayling conditions (A, B and C), the two radiation conditions (OFF and Wi-Fi exposure) and the gender (male and female) as the between subjects factors. The effects of the interactions between the factors were also taken into consideration. In cases where statistically significant effects were discovered, multiple post-hoc pairwise comparisons were applied with Bonferroni corrections. Statistical significance was set at the 0.05 level.

3. Results

Figure 1 shows the ERP waveforms at the FPz lead averaged over all measurements and over the three different Hayling conditions. The perpendicular dotted lines show the time window (220–500 ms) within which the P300 component was sought. The subjects' ERP patterns at the specific electrode are characteristic of the patterns at virtually all the electrodes. The pattern of the ERPs at condition B is quite distinct from the ones at conditions A and C. There is, for all the conditions, a clearly defined P300 component. Post-hoc comparisons showed that the P300 amplitude values at condition B are lower than at both conditions A and C, while conditions A and C are practically equal. Specifically, differences between conditions A and B achieve statistical significance at 18/30 leads, which (as Fig. 2 shows) form a cohesive network.

Exclusively within Hayling condition B, a significant Gender X Radiation interaction effect is manifested. The nature of this interaction is clarified in Fig. 3 which shows the mean P300 amplitudes at the CP6 lead for male and female subjects at the presence and absence of the Wi-Fi signal. In the absence of the Wi-Fi signal, male subjects had greater P300 amplitudes than female subjects, but the difference was not statistically significant. Switching the Wi-Fi signal on significantly reduces

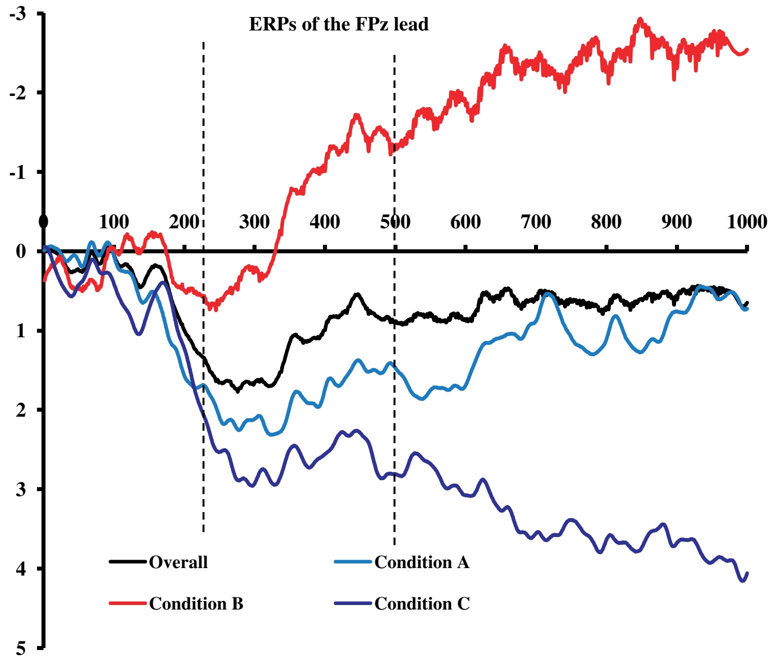

Fig. 1. Average ERP waveforms at the FPz lead for the overall measurements and for the three different Hayling conditions. The perpendicular dotted lines show the time window within which the P300 component was sought.

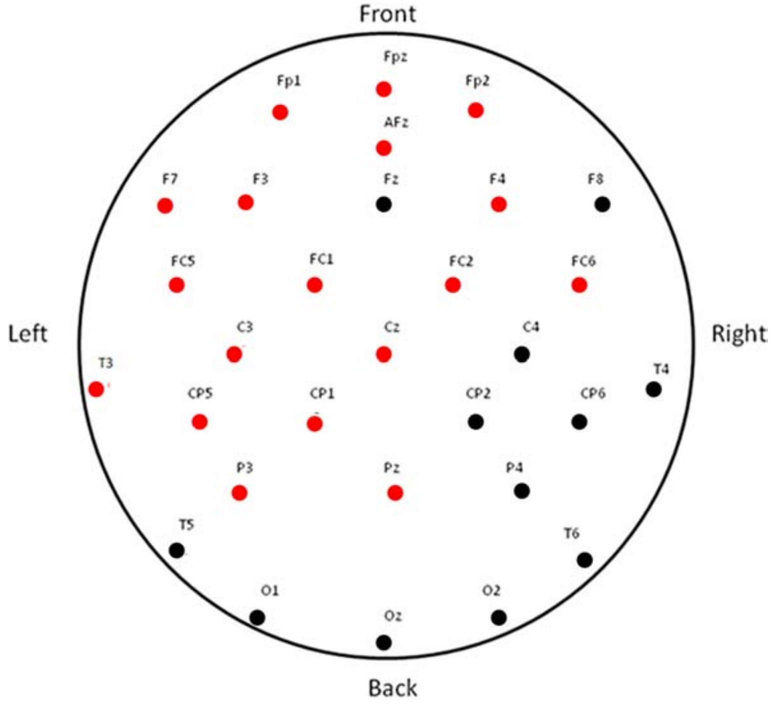

Fig. 2. Comparisons of the P300 component between conditions A and B. Leads at which differences are statistically significant are shown in red.

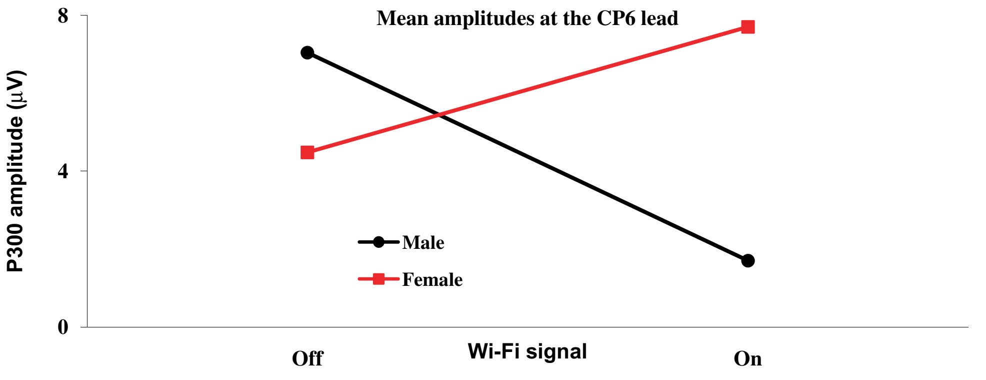

Fig. 3. Mean P300 amplitudes at the CP6 lead for male and female subjects at the presence and absence of the Wi-Fi signal at Hayling condition B.

the P300 amplitudes of the males, while that of the females is enhanced. As a consequence, at the "on" condition, the P300 amplitude of the males is significantly lower than that of the females. The behavior depicted in Fig. 3 is the same for the other leads. As a result of this pattern, while at the "off" condition, there were no significant differences of the P300 amplitudes between males and females (except for electrode AFz), at the "on" condition (as post-hoc pairwise comparisons with Bonferroni corrections proved) significant differences were observed at 15/30 electrodes (Table 2). These leads, as well as the corresponding activation maps, where statistically significant differences between the two genders occur, are shown in Fig. 4.

4. Discussion

There is a significant interaction effect of the gender X radiation that is exclusively manifested in Hayling B condition; this is due to the relative reduction of the amplitudes for the male subjects at the "on" in comparison to the "off" radiation condition and the relative increase in the respective values for the female subjects. As a result, the P300 amplitudes of males are significantly lower than of females at 15 electrodes at the "on" condition.

The comparison between experimental conditions of a modified version of the Hayling Sentence Completion test adjusted to induce WM showed a reduced activation of the P300 component during the inhibition condition (B), than at both the initiation (A) and baseline (C) conditions, while conditions A and C are practically equal. The Hayling condition effect was significant at 18 of the 30 leads over widespread areas of the scalp.

The results of the present study may be interpreted in the light of the psychophysiological and brain-imaging studies related to the P300 ERP waveform and the Hayling test. It has been suggested that P300 originates from task conditions involving working memory operation [13, 33]. In addition, P300 amplitude is thought to be sensitive to the amount of attentional resources engaged during the execution

Table 2. Mean ± standard deviations of the P300 component for male and female subjects at the "off" and "on" radiation condition in Hayling condition B. *p*-values in bold denote statistically significant differences.

	OFF			ON		
Leads	Male	Female	*p*-values	Male	Female	*p*-values
F7	0.74 ± 5.14	2.58 ± 4.57	0.31	1.77 ± 4.50	2.34 ± 4.73	0.74
FC5	2.56 ± 3.19	2.34 ± 4.55	0.88	1.12 ± 2.82	2.79 ± 4.25	0.23
C3	5.62 ± 5.45	2.77 ± 5.34	0.16	1.79 ± 6.53	5.64 ± 4.72	0.08
CP1	2.73 ± 3.34	2.37 ± 4.96	0.81	0.51 ± 2.45	3.43 ± 4.16	**0.03**
P3	2.89 ± 3.78	2.11 ± 4.82	0.63	0.28 ± 2.41	2.84 ± 3.46	**0.03**
Fpz	2.25 ± 3.63	2.08 ± 4.57	0.91	−0.25 ± 2.60	3.12 ± 4.17	**0.02**
Afz	0.62 ± 4.38	4.69 ± 5.71	**0.04**	1.83 ± 5.37	2.94 ± 6.29	0.62
Cz	1.38 ± 3.76	3.63 ± 5.17	0.18	0.74 ± 4.43	2.40 ± 5.42	0.38
O1	2.88 ± 3.55	2.18 ± 4.61	0.65	0.52 ± 2.61	3.19 ± 3.51	**0.03**
O2	2.55 ± 3.73	1.36 ± 3.75	0.39	−1.18 ± 2.83	2.65 ± 3.75	**0.00**
F8	2.54 ± 3.78	0.90 ± 4.67	0.30	−0.21 ± 3.18	1.89 ± 3.24	0.09
FC6	1.21 ± 3.56	2.94 ± 4.59	0.26	0.26 ± 4.48	3.38 ± 5.11	0.09
T4	1.55 ± 3.60	2.86 ± 4.49	0.38	−0.09 ± 6.02	3.73 ± 4.03	**0.05**
CP2	2.70 ± 3.67	2.19 ± 4.59	0.74	0.40 ± 2.92	2.91 ± 5.06	0.12
P4	2.94 ± 3.89	1.94 ± 4.72	0.53	0.76 ± 2.65	2.97 ± 3.93	0.09
CP6	7.04 ± 5.96	4.48 ± 4.90	0.21	1.70 ± 5.59	7.70 ± 6.38	**0.01**
T6	2.14 ± 3.74	2.38 ± 4.54	0.88	−0.36 ± 3.13	3.47 ± 4.66	**0.02**
F3	1.62 ± 3.60	1.82 ± 4.48	0.89	−0.78 ± 3.55	1.70 ± 3.05	**0.05**
FC1	2.29 ± 3.62	2.88 ± 4.07	0.68	0.50 ± 3.00	3.17 ± 3.96	**0.05**
T3	2.18 ± 3.87	2.01 ± 4.54	0.92	−0.35 ± 2.85	2.93 ± 4.59	**0.03**
CP5	2.53 ± 3.59	1.84 ± 4.50	0.65	0.22 ± 2.34	2.67 ± 4.21	0.07
T5	1.78 ± 3.47	1.38 ± 4.32	0.78	−0.50 ± 2.01	2.03 ± 3.51	**0.03**
FP1	0.71 ± 4.31	3.92 ± 6.09	0.11	2.47 ± 5.62	3.72 ± 7.92	0.63
FP2	1.24 ± 5.21	5.06 ± 5.85	0.07	3.26 ± 5.98	2.27 ± 7.31	0.69
Fz	6.09 ± 7.28	4.27 ± 5.96	0.46	3.29 ± 4.84	3.50 ± 2.86	0.89
Pz	2.50 ± 3.88	1.89 ± 4.50	0.70	0.60 ± 2.11	2.18 ± 4.10	0.21
Oz	2.83 ± 3.63	1.05 ± 4.08	0.22	−0.34 ± 2.76	2.16 ± 3.40	**0.04**
F4	1.50 ± 3.73	3.37 ± 5.28	0.27	0.11 ± 3.87	2.61 ± 4.87	0.14
FC2	2.48 ± 2.99	3.22 ± 4.33	0.59	−0.09 ± 3.01	3.44 ± 4.37	**0.02**
C4	2.67 ± 3.81	2.74 ± 4.02	0.96	0.19 ± 4.04	4.42 ± 4.67	**0.01**

of a task [25, 35]. It is postulated that difficult processing tasks that induce high cognitive demand limit attentional resources to resist inhibitory control and produce smaller P300 components [48].

Studies attempting to identify the cerebral generators of the P300 provide evidence that P300 is seen simultaneously, with uniform latency, over widespread areas of the scalp [54] and suggest also, either that it is produced by multiple, relatively independent generators, or that it is a reflection of a central integrated system with widespread connections and impact throughout the brain [14, 44]. However, it is believed that frontal generators are more involved in automated orienting, while temporoparietal generators are more responsive to stimuli, requiring more effort [58].

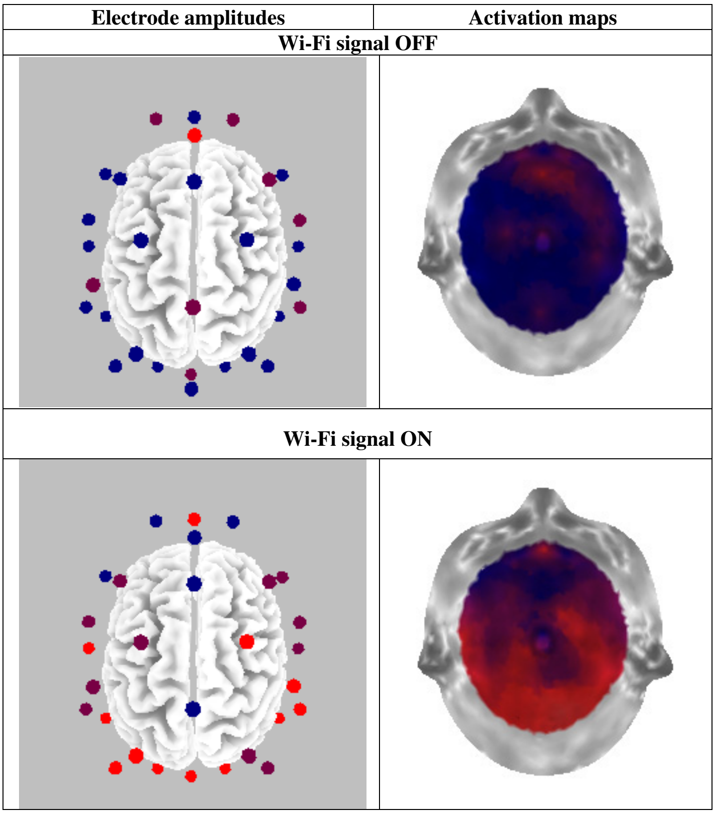

Fig. 4. Comparisons of the electrode amplitudes (left) and activation maps (right) of the P300 component between male and female subjects at the presence (top) and absence (bottom) of the Wi-Fi signal at Hayling B condition. Red color denotes statistically significant differences between the two genders.

In reference to the Hayling test, Collette *et al.* [9] applied PET methodology and found a greater frontal activation during the inhibition than the initiation condition. They attributed the greater activation in the inhibition condition to the complexity of the procedure that involves additional cognitive processes than the processes in the initiation condition that includes planning, semantic search, manipulation of information, selection and evaluation of the response.

Conversely, Nathaniel-James *et al.* [42] using also PET during the application of another version of the Hayling test, found increased activity in prefrontal areas during the initiation as compared to the inhibition condition. A potential explanation provided by the authors is that the initiation condition might rely less on high levels of linguistic processing and more on low levels of word production, generating a functional pattern that could lead to higher frontal activation.

The inconsistency between the findings of the two studies was thought to result from differences in the modified forms of the Hayling test applied in the studies [9]. The Hayling test measures executive functioning and in this regard, although it has been suggested that the prefrontal cortex possesses a pivotal role in executive control [32, 57], research evidence emphasizes the importance of additional brain areas, such as broad cortical and subcortical networks, including thalamic pathways [27]. This broader view might result from the fact that the tests applied for assessment of executive functioning are complex and induce a wide range of skills, thus complicating efforts to identify a unitary interpretation framework.

In the EMF "off" condition, female subjects had significantly lower P300 amplitudes than male subjects. The obtained results may be interpreted in terms of the "neural efficiency hypothesis", which postulates a more efficient use of brain resources in people who are more skilled (trained) than those less skilled [20]. This is in accordance with the notion that a linguistic-related executive functioning has a stronger effect on women than on men [7, 28, 30], and indicate that attentional resources processing when WM updating is engaged during a go and no-go linguistic task undergoes stronger facilitation in women than in men. It is worth noting that previous studies demonstrated also that P300 amplitudes were greater in males than females, supporting the notion that the P300 is sensitive to gender. For example, Oliver-Rodriguez *et al.* [45] studying facial attractiveness and its emotional component, found that P300 amplitudes were greater in male participants.

The relationship between gender and the P300 has been controversial, as some studies found no gender differences [8, 23, 39, 56, 59]. These contradictory findings are difficult to explain. One hypothesis could be based on the account that the difference between the two genders concerning the P300 patterns is attributable to the size and geometry of the head rather than to actual biological and physiological differences [21]. Other possible explanations are seasonal variation [12] and emotion [39, 59]. Furthermore, it has been suggested that hemispheric asymmetry and/or brain lateralization might contribute to these differences [34, 49, 56].

The effect of RF exposure (reduction of amplitudes of the P300 for males and the reverse patterns for females) are in accordance with several studies of our team, regarding gender-related differences in the EEG under 900 MHz and 1800 MHz EMF exposure, similar to that of mobile phones, although the present cognitive task differed from the previous one [24, 41, 46]. Also, Smythe and Costall [53] have reported sex-dependent effects of EMF exposure on the human memory during a memory task.

Emerging evidence provides plausible mechanisms for the explanation of these differences. In particular, central nervous system effects of EMFs have been considered to be secondary to damage to the blood–brain barrier (BBB) permeability [50–52]. It is reasonable to consider the existence of gender-related blood barrier differences, a fact which would explain the fundamental differences between males and females in the intrinsic cognitive processes and in the way they are affected by different types of electromagnetic radiation. Other studies indicate that EMF exposure affects melatonin release. Specifically, a reduced excretion of the urinary metabolite of melatonin among persons using a mobile phone for more than 25 mins per day has been demonstrated [4]. In a study of pubertal individuals, it has been found that nocturnal and diurnal 6-sulfatoxymelatonin excretion is higher in girls [16].

5. Conclusions

To the best of our knowledge, this is the first attempt to investigate the immediate effects of Wi-Fi signals upon brain operation, specifically on the P300 ERP component. Our investigation revealed that P300 amplitude values are decreased for males and increased for females during exposure while performing a Hayling Sentence Completion task. These gender-related differences provide further support to previous studies of our team conducted under different exposure conditions and different auditory tests. As far as the different Hayling tasks are concerned, results show significantly decreased amplitude values for the response inhibition condition in a large area of the brain.

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